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2D LT BOHAN HUMPHREY M

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The Space Debris Problem and Solutions, Specifically the Disposal of the Centaur Rocket Body after Use

Humphrey Bohan
Masters of Engineering, Space Operations
Creative Investigation

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Abstract

This creative investigation explores the problem of space debris in the near-earth environment. This includes the current situation, policies put forth by different organizations, and future trends. There is also an in-depth analysis of the Centaur second stage launch system, the threat it poses as space debris, and methods of removing it as a debris threat from geo-transfer and super-synchronous orbits.

The evaluation of the space debris problem yielded a near consensus that, although the problem has not yet reached dangerous proportions, the future trend predicted by computer analysis is in the direction of dangerous increase. Although shielding and avoidance technology are advocated by many groups, the number one idea put forth to stop the space debris problem is prevention. There is also a nearly unanimous appeal for international policy to ensure prevention of new debris and preservation of an equal floor for competitive space industry.

After careful analysis of the Centaur system and a computer drag simulation for different scenarios, the ideal way to remove the spent Centaur rocket as a debris threat from geo-transfer orbit is to orient the booster into a position where drag will be the largest (longitudinal axis perpendicular to the direction of motion), and circularize the spent booster as much as possible at perigee. At this low altitude (only 227 km!), the lifetime of the booster is reduced far below the 25-year mark set by the 1995 revision of the 1989 Report on Orbital Debris. From super-synchronous orbit, the best solution is to conserve a small amount of fuel and circularize the orbit at a super-synchronous altitude, successfully removing it as a threat to any spacecraft (since the amount of traffic beyond GEO altitudes is negligible). The analysis presented on the Centaur system is easily converted to almost any system of similar mission and can provide a basis for future analysis of any system.

Background

The information presented in this paper on the problem of space debris is a conglomeration of numerous reports and studies that have been made on this topic over the past decade or so. As the years have progressed, interest in the problem of space debris has increased dramatically. Recent serious collisions have increased concern over the need for evasion abilities and shielding on satellites to avoid the possibly crippling effects of collision with space debris. The idea of an on-orbit debris-collection device has also been explored as a means of clearing the debris already orbiting earth. Because of the cost and, for many missions, unfeasibility of these approaches, there has been more serious discussion about decreasing the amount of debris being created in orbit. While avoidance and shielding does help to protect satellites and indirectly prevent the creation of more debris (an aspect I will explore), the current rates of production due to launch and operations procedures will quickly make even this approach insufficient. Many studies have concluded that the only efficient approach is direct prevention. It is this approach that I will focus on in this paper.

The Centaur upper stage rocket was first conceived of in 1957, at the dawn of space exploration, as a means of getting very heavy payloads into orbit in the shortest possible time [1]. The project was developed by General Dynamics (now part of Lockheed-Martin Corporation) and was the nation's first high-energy upper stage launch vehicle [1]. The Atlas and Titan rockets are commonly used first stages for the Centaur attachment, which measures 8.8 meters in length and 4.3 meters in diameter [2]. Shown in Figure 1 is a picture of a Titan IV launch, with a Centaur second stage in the upper fairing. Figure 2 is a schematic of the positioning and relative size of the Centaur.

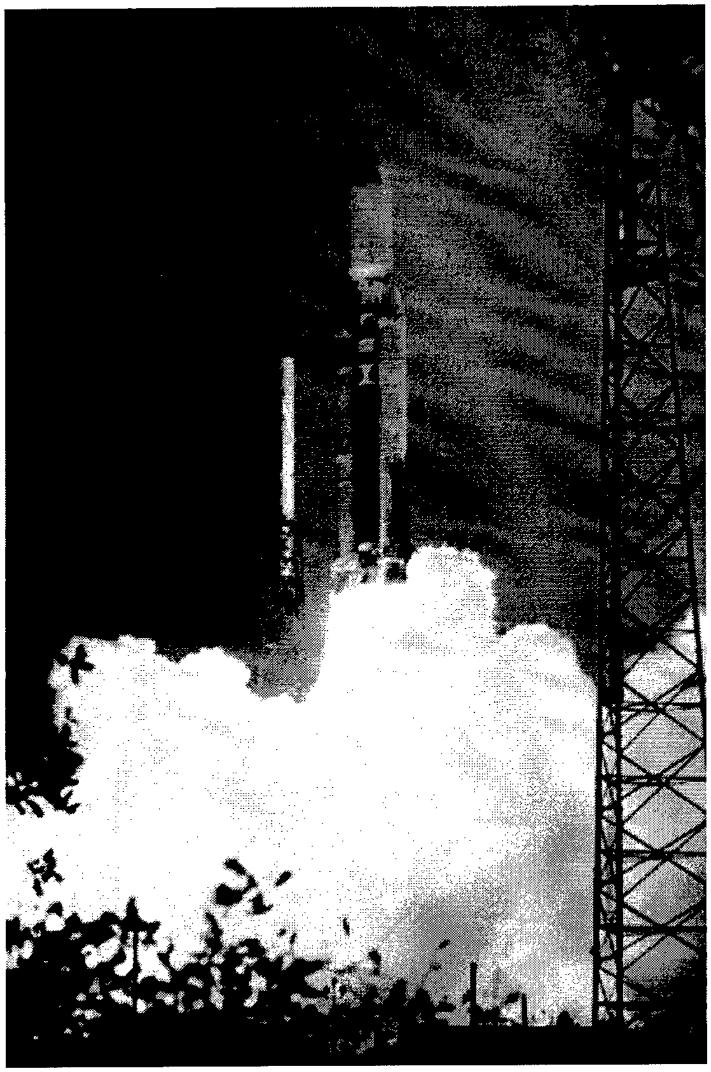
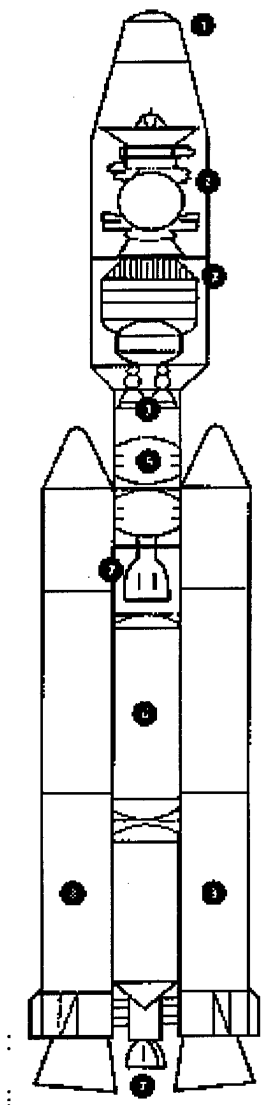


Figure 1: Titan IV Launch [3]

The Titan IVB/Centaur Rocket



1. Payload Fairing (McDonnell Douglas)

Length: 20.1 m (66 ft)
Diameter: 5 m (16.7 ft)
Structure: Aluminum isogrid

2. Cassini Spacecraft (JPL)

3. Guidance and Navigation (Honeywell)

Guidance computer and control system, including ring laser gyroscope

4. Centaur Upper Stage (Lockheed Martin Astronautics)

Length: 8.8 m (29 ft)
Diameter: 4.3 m (14 ft)
Propulsion: 2 engines (Pratt and Whitney)
Propellant: Liquid hydrogen and liquid oxygen
Thrust: 147,000 N (33,000 lbf)
I_{sp}: 444 sec

5. Titan IVB Lower Stage

6. Liquid-Propellant Rockets (Stage I and Stage II) (Lockheed Martin Astronautics)

Length: 36 m (118 ft)
Diameter: 3 m (10 ft)
Structure: Aluminum skin (Stringer)

7. Stage I and Stage II Engines (Aerojet)

Propellant: N204-Aerozine 50
Thrust: Stage I: 2.4 million N (548,000 lbf, total for 2 engines). Stage II: 467,000 N (105,000 lbf)
I_{sp}: Stage I: 302 sec, Stage II: 316 sec

8. Solid-Propellant Rocket Motors (Alliant Techsystems)

Length: 34.3 m (112.4 ft)
Diameter: 3.2 m (10.5 ft)
Thrust. 15.2 million N (3.4 million lbf. total for 2 motors)
I_{sp}: 286 sec

Figure 2: Titan IV/Centaur Schematic [2]

The Centaur runs on two main engines, both designed by Pratt & Whitney Aircraft [1]. The two RL10 engines produce 16,500 pounds of thrust each and run on a combination liquid oxygen/liquid hydrogen propellant that produce an I_{sp} of 444 seconds [2]. These engines are also capable of making multiple starts after long coasting periods, which gives them a lot more flexibility for correcting the orbit mid-course [1]. The Internal Navigation Unit (INU) provides attitude control and navigation for the first stage (when used with the Atlas) and for itself after separation from the first stage, further enhancing its maneuverability [4]. Several small thrusters, in addition to the two main engines, provide the muscle to the Reaction Control System (RCS) which physically makes these corrections [1].

Given its varied abilities, the Centaur can be used to transfer satellites to almost any desired orbit, even geostationary orbit (at approximately 35786 km from the surface of the Earth) [5]. When the Atlas II/Centaur launch system boosts a satellite into geostationary orbit, the Centaur usually enters what is called a geo-transfer orbit after disengaging from the Atlas booster [5]. This orbit is highly elliptical, with its point of closest approach to the earth (perigee) at approximately 227 km (122.6 nm), and its furthest point from earth right near geostationary altitude (35703.4 km or 19278.3 nm) [5]. In this orbit, it takes approximately 75 years (!) for the booster to degrade enough in its orbit due to drag to begin reentry to the Earth's atmosphere and burn up [6]. For those 75 years, these useless rocket bodies orbit purposelessly around Earth and provide a dangerous collision threat to any satellite within their orbits, as well as providing a great deal of possible debris mass if a booster is broken apart for any reason.

Introduction

The launch of Sputnik by the Soviet Union on October 4, 1957 began the space race between the United States and the Soviet Union. It also began mankind's pollution of space. The Soviet Union's policy of exploding satellites at the end of their lifetime, as well as the littering caused by connectors, bolts, disposable booster rocket bodies, and non-operational satellites has created a near-Earth space environment that contains tens of thousands of man-made objects ranging from flecks of paint, to a screw driver, to Centaur rocket bodies. Since Sputnik (as of January 1996), mankind has launched over **4500** spacecraft (3750 separate launches) into Earth-orbit [7]. There are approximately 8,500 man-made objects that are currently being tracked by the North American Aerospace Defense command (NORAD), only 6% of which are operational satellite systems [8]. In addition, based on explosion modeling, there may be as many as 100,000 pieces of space debris that are too small to be detected from earth (about 10cm in diameter for close orbits, 1m in diameter for debris at geostationary altitudes) [8]. Since collisions among space debris and other earth-orbiting objects create more debris, the increase can become exponential as the probability of collision in the more popular orbits becomes higher. Over time, this could theoretically make some orbits completely unusable as the probability of collision in those regions approaches one for normal operational lifetimes. Only actions taken now to prevent the accumulation of more useless mass in space can avert this unacceptable future.

Despite the increasing severity of the space debris problem, there is, at this time, no coordinated effort by any of the space-faring nations of the world to mitigate space debris creation in any but the most vague and voluntary way. However, there have been investigations by several independent agencies into the problem of space debris and they have presented the possible solutions available to us. One such agency, the Defense Research Agency (DRA), suggests, as many have, that satellites be deorbited after their lifecycles have ended so that they burn up in the atmosphere instead of forming space debris [8]. This requires some sort of direct action, be it using some sort of propulsion device to lower its orbit or somehow increasing its drag so that it degrades "naturally" more quickly. It is the deorbit approach to the mitigation of space debris that I will be focusing on in this report.

In analyzing the mitigation of space debris through the deorbiting of space systems that are past their operational life, it will be helpful to spend some time looking at a particular system and the challenges that present themselves in changing that system. In this regard, I shall provide a detailed analysis of what would be required to deorbit the Centaur booster rocket body after use, including the physical changes to the rocket, how those changes affect performance and cost, and what changes to policy and operations are required to make use of these alterations effectively.

Currently, used Centaur rocket bodies are often left to orbit the Earth for about 75 years in a geo-transfer orbit (GTO) until they finally burn up in the atmosphere (they are occasionally placed into super-synchronous orbits instead, which I will discuss later). During this time, the empty booster orbits through every altitude between about 230 km and about 35700 km. This makes this particular booster particularly dangerous since it can theoretically collide with almost any other space system in orbit at its inclination (usually about 26.5°) [5]. In my analysis, I will discuss what design changes can be made to the Centaur (and, by extension, to other boosters as well) in order remove it as a space debris threat and decrease the chance of collision with other space systems.

As I have stated, I will, through the course of this paper, discuss in some detail the space debris problem: past, present, and future. I will also look briefly at policy changes and further possible solutions to this problem that can be implemented at every level of world's space programs, from national and international policy to individual design and operation. Finally, I will focus more specifically on one system, the Centaur second stage rocket, and evaluate in detail what changes must be implemented to safely and efficiently dispose of this system in the most cost-effective manner after it has accomplished its mission. I will also evaluate at what possible cost (in terms of money, risk, and complexity) all of the options for change will incur. On the whole, this paper should provide a good outline of what the current situation is and what our options are for the future, as well as a detailed assessment of the changes that must be made for the Centaur system when it is launching a satellite to geostationary orbit.

Specific Topics of Review

Space Debris Problem

Thousands of pages on the topic of space debris and possible solutions to this problem have been written since the late 1980's / early 1990's. For the purposes of this paper, however, I will only address the major issues and focus on the details that pertain to my later study of the Atlas II/Centaur system.

As stated earlier, space debris has been a part of the near-Earth space environment since the beginning of space exploration. The problem it presented, however, was seen in all its "glory" on July 24, 1996. On this date, at approximately midday, the French CERISE microsatellite (launched a year earlier as a secondary payload on Ariane flight 75) suffered a sudden change in attitude [9]. Subsequent observations concluded that CERISE's stabilization boom had been struck by a piece of orbiting space debris [9]. Using Satellite Tool Kit (STK), AGI's satellite database, and NORAD's Two Line Element sets, it was determined that the piece of the debris most likely to have collided with CERISE was ARIANE BOOSTER DEBRIS from a launch in 1986, travelling at a relative velocity of over 31,000 mph [9]. The Ariane booster debris was created years before when residual propellant left in the tanks accidentally ignited and exploded the rocket body [10]. A piece of a booster that had been left in orbit after use had, a **decade** later, nearly destroyed an operational satellite! This collision (the first in history between two cataloged objects in orbit) spurred more discussion on the problem of space debris and is a prime example of why analysis on deorbiting the Centaur rocket body is of great importance and relevance [11].

Although this was definitely the most dramatic example of the effects of increasing space debris levels, it is by far not the **only** example. Every time the space shuttle returns from a voyage, there is damage from very small debris fragments impacting the structure, including loss of tiles and small dents in some of the windows [11]. It is also known that the severing of the Small Expendable Deployer System (SEDS) tether (which was 5mm wide and 20 km long) was caused by some kind of space debris after only *four days* in flight in 1994 [12]. The threat of collisions in space is moving from theory to reality at an alarming rate.

Current Policies, Procedures, and Changes

In the past decade and a half, there have been several important studies on the topic of space debris. The American Institute of Aeronautics and Astronautics (AIAA) Technical Committee on Space Systems released one of the earliest studies in July of 1981. In this paper, they pointed out that the majority of time and effort was being spent on studying the hazard level of certain debris and predicting the propagation of debris through time instead of focusing on "satellite design and strategies to minimize the short-term and long-term effects of debris deposition" [13]. Recognizing the problem of space debris as a self-perpetuating and potentially exponential problem, the AIAA recommended several important changes in space operations and design. They suggested that NASA, the DoD, and other organizations should begin evaluating debris control techniques and that a dialog should be initiated among the space-faring nations of the world to develop "practical design and operating standards and regulatory policies" [13]. As part of their conclusion, the AIAA also listed several changes to be made to space vehicle design, which included several defensive techniques to avoid losing the satellite to debris collisions and a suggestion that space systems be disposed by retrieval, earth reentry, earth escape, or transfer to "dump" regions or less-often-used orbits. In general, the findings of the AIAA were that the most effective method of positively impacting the space debris problem is by "constraining the generation of further debris," which is exactly the solution I will present for the Centaur [13].

One of the most comprehensive studies on the problem of space debris was the 1989 Report on Orbital Debris (and its 1995 revision) [14]. The original report prompted the National Space Policy Directive-1 (NSPD-1) on November 2, 1989 [14]. On the topic of space debris, this policy states:

> *"All space sectors will seek to minimize the creation of space debris. Design and operations of space tests, experiments and systems will strive to minimize or reduce accumulation of space debris consistent with mission requirements and cost effectiveness. The United States government will encourage other space-faring nations to adopt policies and practices aimed at debris minimization."* [15]

Although this mentality is a good one, the directive is much too vague to have any effect. Calling on all space sectors to "strive to minimize" debris only when it is cost-effective leaves too much room to avoid change. As the analysis of the Atlas/Centaur system will demonstrate, introducing a deorbiting capability **will** decrease the performance of the system and/or cost more money. This is true, in the short term at least, of **all** measures to decrease the amount of space debris. Even though this policy is purely voluntary at this point, it has made a difference in government-run programs in the United States, particularly NASA, Air Force, and US Space Command missions. The directive prompted the U.S. to modify its booster rocket disposal procedures in order to decrease production of space debris. Modifications to the Delta upper stage, as well as other implemented changes, have reduced the U.S. contribution to debris fragment accumulation through disposed connectors, bolts, and aluminum oxide particles to nearly zero [12]. However, a great deal more needs to be done.

The 1995 revision of this report provided an updated view of the problem, and the solutions available to the international community. For mitigation, it suggested the use of lanyards to attach explosive bolts and the like to the spacecraft/booster, the elimination of the production of aluminum oxide (Al_3O_2) particles by solid rocket motor propellants, and the de-gassing of boosters so that there is no chance of explosion later in life (like the Ariane booster that eventually collided with the CERISE microsatellite). Furthermore, the report suggested that those boosters that can be de-orbited or placed into "graveyard" orbits at the end of their useful lifetimes, removing a large amount of potential debris mass from the space environment. Since many spacecraft have a performance margin built into their propellant budgets, the report suggests that this fuel may be used to execute a de-orbit burn, with the only possible modification being the additional guidance control needed to direct the burn in the correct direction [12].

Alternatively, the report suggests that disposal of space devices in a transfer orbit (with solid rocket motors) may be able to use an off-axis burn to reduce the perigee enough to cause the craft to reenter eventually (another option I will explore later for the Centaur), for about a 15% performance penalty for the system. To quantify that statement, the report concludes that reducing the lifetime to less than 25 years is sufficient to remove a spacecraft or booster as a potential threat [12].

The National Research Council (NRC) of the National Academy of Sciences released a study on June 13, 1995 on the increasing risk spacecraft face from orbital debris. One of the most notable conclusions presented was their opinion that international efforts are needed *immediately* to develop debris mitigation techniques through operations and design. They suggested that the tethering of normally released objects (lens covers, clamps, etc.) and the maneuvering of rocket stages and spacecraft out of heavily-trafficked orbits after use will be necessary to constrain the long-term growth of the debris population. In a scary scenario, some suggested that even if all launches were to cease, the existing space debris population would, through collisions with itself, increase exponentially over time. Although de-orbiting boosters does not address this problem, it does show how important it is not to **add** to the problem, if we are ever going to deal with the problem we already have. In fact, the council specifically suggested that spacecraft and rockets in LEO should be maneuvered to less-frequently-trafficked regions or execute a final burn that will cause them to reenter the earth's atmosphere and burn up [16].

A more recent study on space debris (and the last one I will present here, although there are more) was the Second European Conference on Space Debris. From March 17-19,1997, more than 200 experts from 18 different countries met in Darmstadt, Germany, to discuss this very problem. In general, the group presented papers on the current debris situation and made recommendations on the measures and guidelines that should be used in addressing the problem. The papers dealt mainly with the risk of collisions with operational satellites and manned space flights. Seeing the situation much as the aforementioned groups did, the experts concluded that the "only way to achieve debris mitigation is prevention" and that "all efforts should be directed towards minimizing the creation of new space debris" [17]. As other groups have stated, the experts stressed the need for international cooperation on this topic and stated that the Inter Agency Space Debris Coordination Committee (IADC) will play a key role in assessing the most cost-effective ways to achieve these results [17]. A representative of the British National Space Centre (BNSC) to the conference, Richard Tremayne-Smith, stated:

> "We have had a mandate since the early 1990's to be proactive in this area. Last year Britain formally joined the Inter-agency Debris Coordination group in its own right. Since the CERISE satellite was hit, everyone is taking space debris a lot more seriously. It is important to make sure the message gets through to industry." [8]

The DoD, NOAA, INTELSAT, European Space Agency, National Space Development Agency of Japan, NASA, and others have already contributed to mitigating debris creation. One way in which they have all committed to preventing the creation of more debris is by boosting aging GEO satellites to so-called "graveyard orbits." These orbits are suggested to be at least 300 km above the geosynchronous orbit altitude, high enough that there is no chance of future interference with satellites in GEO. For space objects in GTO (geo-transfer orbit), into which the Centaur booster is often launched, there is also the beginnings of an effort at debris prevention. Japan initiated this plan when, on August 28, 1994, it de-orbited the second stage of its H-II launcher from a GTO orbit of 251 km X 36,346 km down to an orbit of 150 km X 32,298 km with an idle mode burn [18]. The emptied booster eventually fragmented into at least six pieces, all of which have since decayed. This approach is one of the suggestions I will make later in this paper for the de-orbiting of the Centaur booster from GTO.

The Future of Space Policy

The reason there is a space debris problem at all is that the creation of debris is that the easiest way of dealing with spent space systems and devices is not dealing with them at all. As I will outline in the next section, after the Centaur is de-gassed, the operators don't know and don't care where it is. The only one watching is NORAD, who will have to watch it and the dozens of other Centaur boosters that have been launched into geo-transfer orbits for decades to come. Until there is an incentive to make these changes (through legal and/or financial pressures), there is little chance that such a voluntary policy will make a difference in non-government procedures. As I have stated, there have been some important changes in mind-set the past decade or so on the part of many governments' space agencies. But in this world of more and more commercial space venturing and contracting, government-only adhesion to the policy of debris mitigation and prevention provides little comfort to the future. The problem is not a lack of power on the part of the government to regulate space use. Under Section 202(b)(4) of Title II of the Land Remote-Sensing Commercialization Act of 1992, the NOAA includes a condition under which a company applying for a license must "upon termination of operations under the license, make disposition of any satellites in space in a manner satisfactory to the President" [19]. The section obviously covers the authority of the NOAA to regulate how commercial space programs dispose of their satellites after their usable lifetimes have expired. However, the 1995 revision of the 1989 Report on Orbital Debris makes an important point concerning the government's use of this kind of authority. Stressing again the need for an international consensus on the issue of space debris, the report reminds the U.S. that if the costs and penalties involved in eliminating debris creation are not unilateral among all of the space-faring nations, companies from the U.S. will be at an unfair advantage in the global space market [19].

The conclusion to be drawn about what needs to be done on the policy side of this issue is obvious from the several studies I have analyzed here. There is a desperate need for international discussion on the topic of space debris. The threat of orbiting debris affects the satellites of every space-faring nation, so the responsibility to defeat the threat is the responsibility of all. The U.N. has used the Scientific and Technical Subcommittee of the Committee on the Peaceful Uses of Outer Space (COPUOS) to attempt to address the issue on an international level, but the results have been slow and difficult [18]. A more specialized forum is required to address the issues that face the many nations involved; one that has the authority to bring the group together and force decisions, if need be, with economic or political actions.

As I have discussed, there have been positive changes in U.S. space policy. Since its initiation of the venting of all fuel from spent Delta rockets in 1981, there have been no explosions in space. The French space organization CNES has put policies on the floor concerning the tethering of clamps, the elimination of Al_3O_2 emissions, the venting of excess propellant, and the de-orbiting or planned reentry of used boosters [18]. But as mentioned previously, there needs to be an international decision-making body that makes similar policies concerning all commercial launches as well. Only by world wide implementation of the suggestions laid out here can there be any hope to stop the progression of debris creation and prevent the not-so-distant-future from having only limited and precarious use of the near-earth environment.

Centaur 2nd Stage Launch System

The Centaur rocket is currently launched as a second stage from Cape Canaveral Air Force Station, FL by the 45th Space Wing (latitude=28.5°). In the future, the 30th Space Wing will also launch the Centaur from Vandenberg AFB, CA. When boosting a payload to geosynchronous orbit, the first stage rocket (using the Atlas II as an example) burns its booster and sustainer engines for several minutes (beginning immediately before lift-off) and then burns only the sustainer engine for about five minutes (after the booster engine runs out of fuel). At this time, the Centaur undergoes a pyrotechnic separation from the Atlas booster. The Atlas II retro-rockets (angled at approximately 45° off of the longitudinal axis) then fire, backing it away from the Centaur/payload system and placing it into a ballistic re-entry "orbit". This is a good example of booster disposal, since the Atlas never actually enters into orbit around the earth and quickly (and safely) burns up in the atmosphere. The Centaur then does its first burn to place it into a parking orbit and coasts for about 15 minutes to the equatorial plane. At the equatorial plane, the Centaur executes its second and final burn, which places the Centaur/payload system into one of two orbits: either a geo-transfer orbit with a perigee altitude of about 122.6 nautical miles (227 km) and an apogee altitude at 35703 km (approximately GEO), or a *super-synchronous* orbit with its *perigee* at GEO and its apogee at an altitude up to **two times** GEO (approx. 70,000 km altitude). Either way, the payload then separates from the Centaur and completes the rest of the plane change (from about 26.5°, which is Cape Canaveral's latitude minus the small plane change executed by the Centaur stage, to 0°

for GEO orbit). The Centaur then performs a "collision and contamination avoidance maneuver." This maneuver uses a hydrazine reaction control system thruster to back away from the payload. In a second maneuver, the ground station commands the Centaur to open its propellant tanks in such a way that the pressure "blows down" any residual propellant, which consists of liquid oxygen and hydrogen, and any residual hydrazine from the collision avoidance maneuver. During this maneuver, attitude control is maintained so that the propellant is vented at a 90° angle to the orbital plane of the payload, further aiding in moving the Centaur away from the payload. However, this de-gas procedure is done mainly to prevent the possibility of explosion of the Centaur at any future time during its long afterlife in orbit. Then ground control orders the Centaur to shut down completely, and it is left dead in orbit [5].

There are two distinct ways in which the Centaur operates when placing a satellite into GEO orbit. A "minimum residual shutdown" is executed if the payload uses the same liquid fuel reserve for its final positioning maneuver after detachment from the Centaur and for station-keeping maneuvers during its operational life. For this maneuver, the Centaur tries to get as high an apogee as possible (usually about 35,000 km X 70,000 km altitude orbit, but could have a lower apogee if the Centaur does not operate optimally), so that the residual plane change that the payload completes is done at as high an altitude as possible to cut down on the amount of fuel used (Δv for plane change maneuvering decreases as the altitude increases). In this case, the Centaur burns all of its fuel getting to as high an apogee altitude as possible, leaving no residual fuel (except the hydrazine used in the collision and contamination avoidance maneuver). For satellites not requiring this maximum-burn maneuver, the Centaur may have a significant amount of fuel left over to be vented. The Centaur is always launched with a "full tank of gas," so the amount of fuel left over is determined solely by how well the Centaur performs (and whether or not this type of full-burn maneuver is used). There is always a margin of fuel called "contingency propellant" that represents about 10% of the nominal fuel supply. If the Centaur performs in its expected efficiency, this will be the propellant left over to be vented at the end of life. If the Centaur performs at its maximum, there will be more fuel left over to vent at the final maneuver. The existence of residual fuel may be a factor later on when evaluating the amount of fuel needed to execute some sort of disposal maneuver. This residual fuel may be enough to complete such a maneuver or may at least be able to contribute to the Δv required. Either way, the existence of residual fuel after payload insertion will decrease the cost to include a de-orbiting protocol for the Centaur, and make it a more reasonable proposition to commercial organizations [5].

The Centaur enters into a super-synchronous orbit between 30 and 40 % of the time, depending on what payload is being inserted. For example, the DSCS satellite (Defense Satellite Communications System) has an integrated apogee boost subsystem. This liquid engine is used to get from super-synchronous orbit to GEO (circularization at perigee) and separates after use. Some payloads have a perigee-raising solid motor that can only do a fixed Δv maneuver. This requires that the Centaur detaches at a set position and orbit, which is the geo-transfer orbit mentioned previously [5].

Possible Solutions

In approaching the problem of eliminating the threat the Centaur poses as space debris, several solutions present themselves. Theoretically, one could disintegrate the empty booster with some sort of directed energy device. When the booster is in GTO, it could be boosted beyond the GEO altitude by doing an apogee-raising maneuver (and circularization), or it could execute a perigee-lowering maneuver in order to make it de-orbit much more quickly. Another way to cause the booster to de-orbit more quickly could be to somehow increase the atmospheric drag on the rocket body, thus causing it to de-orbit more quickly on its own (decreasing the ballistic coefficient). When the booster instead starts in a super-synchronous orbit, it could execute a perigee-raising maneuver that would carry the entire orbit outside of the GEO sphere. I will address each of these possible solutions separately and then determine the best course of action. It also must be kept in mind that any actions taken by the Centaur's manufacturers and operators will be done in a world where their competition may not be making similar modifications. Knowing this, any suggestions made should have as little impact on the performance of the Centaur as possible to increase the chance that such suggestions will be heeded. In what is hopefully the near-future, where there is international cooperation in addressing the problem of space debris, and universal enforcement of de-orbiting policy, it will be possible to enforce modifications that will be more effective in the dealing with the problem at hand. These issues will be addressed in the following sections.

Energy Weapon

The first solution idea is disintegrating the booster with some kind of energy device. The Air Force is currently working on a similar idea for destroying the tens of thousands of pieces of small space debris orbiting earth. The idea is to place some sort of energy weapon into orbit which would be capable of targeting and "illuminating" pieces of space debris. This action would either disintegrate the debris so that it no longer posed a threat, or could cause it to enter a lower orbit, thus decreasing its orbital life.

Presumably, the energy would be directed toward the debris in a radial direction such that the energy incident on the debris would cause a change in velocity toward the earth, or directed **against** the object's motion, thus slowing it down and causing it to drop in altitude. This approach may one day be very effective in eliminating the tens of thousands of small pieces of debris that are already in orbit. However, if such a device were to be used on something as large as a rocket body, the force of the blast (which are on the order of pico-seconds in duration) would cause large amounts of debris to be exploded off the other side of the booster. This would only serve to further the problem of space debris, not solve it. Future technology may allow the possibility of destroying such large objects with directed energy, but the technology available in the near future is not adequate to the task being discussed here.

"Graveyard Orbit" (Circularization beyond GEO)

The next approach I will evaluate is the idea of boosting the Centaur into a higher orbit (≥300 km beyond GEO, which is equivalent to a circular orbit with an altitude of at least 36036 km above the surface of the Earth) [18]. I will first look at this option as it applies to the GTO scenario. Considering the orbital parameters of the Centaur, it is possible to determine what change in velocity is required to change the orbit of the booster from an elliptical orbit of 227 km X 35,703 km (altitudes) to a circular (or near-circular) orbit of an altitude of 36,086 km (300 km above geosynchronous orbit, which is the recommended altitude above GEO to avoid any interference with operational systems). The most efficient way to do tangential burns and reach this orbit is by doing a bi-elliptical transfer. First, the Centaur executes a burn that circularizes the orbit at apogee, which is just below GEO. Then, at the opposite side of the orbit (1/2 the period), the Centaur executes another tangential burn that puts it on an elliptical transfer orbit (Hohmann) that brings it back to the original apogee position at an altitude of 36,086 km, which is 300 km above GEO. Then, a final tangential burn circularizes the Centaur at a super-synchronous orbit that is 300 km above GEO during its entire orbit. Figure 3 shows a diagram of this maneuver.

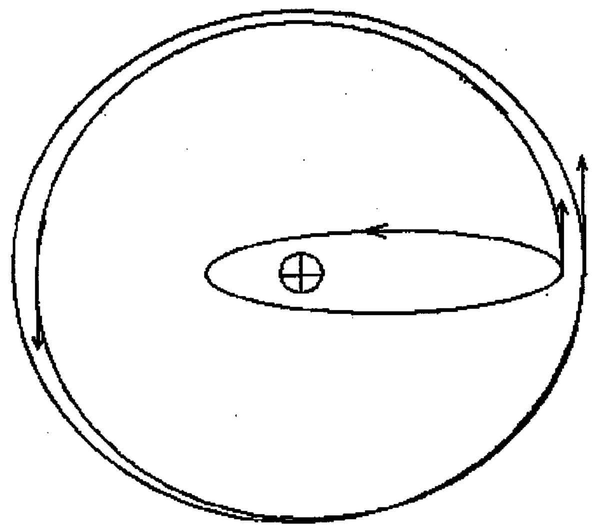


Figure 3: Circularization at apogee (geo-transfer initial orbit)

An orbit of this type has several pros and cons. On the positive side, since all three burns are done at GEO altitudes, such a maneuver would require a total Δv of only 1.48217 km/s. On the negative side, however, there are some pointing issues to be considered, as well as the fact that doing three separate burns requires a great deal of timing, and three extra start/stop operations on the engine. Luckily, the Centaur does have its own navigation and attitude control system on-board, the INU (internal navigation unit), that controls the navigation and attitude control for the whole Atlas/Centaur system and for the Centaur alone after detachment. Since attitude control is possible after separation from the payload (as mentioned previously, the Centaur points itself at a 90° angle from the plane of the payload's orbit when it de-gases), the Centaur can be pointed in the desired direction. However, the RCS engines that provide the pointing ability have a limited fuel supply. Therefore, not only is extra fuel needed to execute the 1.5 km/s in total Δv maneuvers, but additional fuel may be needed for the attitude control thrusters. This makes this solution a possibly costly addition to the Centaur system in terms of loss in payload-boosting ability. Furthermore, this maneuver requires that the Centaur be operational for almost a day after payload separation, a long time for the batteries to be operating. This option can be kept in mind, but it may not be the best solution for this time.

The placing of the Centaur at a circular (graveyard) orbit beyond GEO can be considered much more reasonably for the super-synchronous case as well. Since the perigee is at GEO, and the apogee is at some point up to two times GEO, a circularization at apogee would effectively dispose of the satellite. Figure 4 shows a diagram of this maneuver, where the perigee is at GEO, and the apogee is at two times GEO.

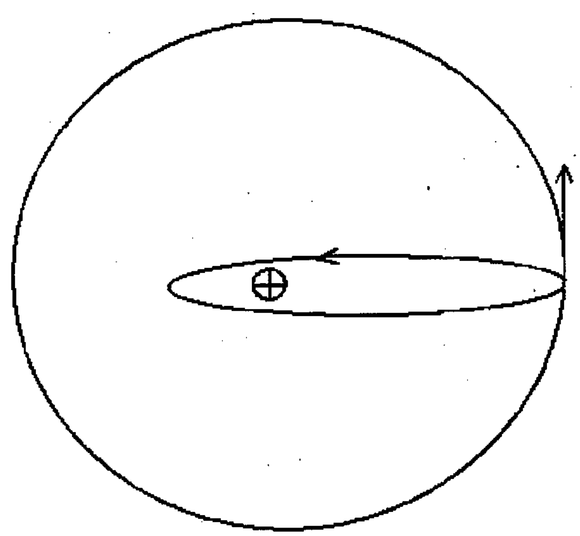


Figure 4: Circularization at apogee (super-synchronous)

The Δv required to perform this maneuver would depend upon the apogee radius, but since the projected orbit is one with an apogee at two times GEO altitude, I will use 84,328 km as the *radius* of apogee to perform the maneuver, since this is equivalent to two times the geosynchronous radius. With this assumption, the calculations run as follows for a tangential burn at apogee:

$V_i = \sqrt{[(2*\mu/r_a)-(\mu/a)]} = 1.77516$ km/s ; where r_a=radius at apogee and a=semi-major axis

$V_f = \sqrt{[\mu/r_a]} = 2.174116$ km/s

$\Delta V_{total} = V_f - V_i =$ **0.39896 km/s** [20]

The Δv would only be approximately 0.4 km/s to circularize the satellite at the apogee altitude. This small Δv requirement could theoretically be accomplished by a relatively small amount of fuel. The only problem is that in this case, the satellite reaches this apogee altitude because the engines are burned clean to attain maximum altitude. If there were some way to save just a small amount of fuel, this maneuver would be easy to accomplish. By adding a small amount of control to the burn procedure, a margin of the fuel can be preserved until the Centaur can be positioned to do a tangential burn at apogee. Normally, there is a small amount of fuel left over (as discussed previously), called the contingency reserve. If the Centaur burns all but this fuel to get to apogee, the contingency reserve fuel could be used to perform the maneuver, and the loss to payload-boosting capacity would be minimal. Another idea is to do the contamination and collision avoidance maneuver in such a way that the maneuver accomplishes (or nearly accomplishes) the desired orbit change. This could theoretically reduce the cost to the Centaur system to zero. Besides the complexity, the only other concern when considering this solution is the fact that the Centaur would need to be operational for about 24 hours after payload insertion. This is a long time to be using battery power, and would have to be a consideration when designing/modifying the Centaur for this kind of debris mitigation.

Circularization at Perigee

Assuming the GTO case, it is possible that circularizing the orbit at perigee would decrease the orbit lifetime to an acceptable length. Placing the satellite at the lower orbit for its entire orbit, instead of just a small portion of it, allows the natural atmospheric drag effects to affect the satellite for its entire orbit. For a perigee altitude of only 227 km, circularizing at perigee would decrease the lifetime significantly, from decades to months [20]. Figure 5 shows a diagram of this maneuver, with the initial perigee at 227 km and the initial apogee at 35703 km.

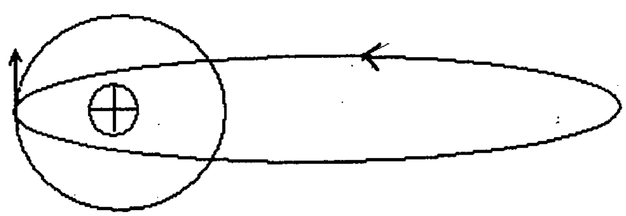


Figure 5: Circularization at perigee (geo-transfer)

Assuming a perigee altitude of 227 km, as stated before, and that the burn is tangential, the calculations run as follows:

$V_i = \sqrt{[(2\mu/rp) - (\mu/a)]} = 10.2137$ km/s
$V_f = \sqrt{[\mu/rp]} = 7.7683$ km/s

$\Delta V_{total} = V_f - V_i =$ **2.4454 km/s** [20]

The maneuver would require a Δv of approximately 2.45 km/s. This would decrease the orbit lifetime of the Centaur from about 75 years to only a few months. As discussed in the United Nations' Report by the Secretariat on the topic of space debris, NASA has stated that it has found an orbit lifetime of 25 years or less would effectively serve the purpose of eliminating the danger of a defunct space system as debris [12]. Keeping this in mind, the lifetime produced by this maneuver would obviously be more than enough to remove the Centaur as a space debris hazard. Also, the fact that there is only one maneuver involved and it takes place soon after orbit insertion relieves a great deal of stress from the batteries. There may be some modifications necessary to sustain the Centaur to the burn position, but the time is much less than that required of the bi-elliptical transfer needed to circularize at apogee. On the down side, however, a 2.4 km/s velocity change requires a great deal of fuel to accomplish. This solution would definitely require a reserve of fuel to be conserved during payload insertion and put aside for deorbit use.

Lowering Perigee (thrust involved)

Another approach to drastically decreasing the orbit lifetime of the Centaur is by lowering the perigee, but keeping an elliptical orbit (Figure 6). This approach is similar to the previous idea, but it may cost less Δv (and therefore less fuel). It may be possible to lower the perigee of the elliptical orbit enough that the increase in atmospheric drag during the time it is travelling through perigee is enough to lower its lifetime to an acceptable number. A circularization at a lower orbit makes the drag a factor during the *entire* orbit, increasing the amount of drag *per orbit*, while this method increases the drag significantly, but only during a fraction of the orbit. Therefore, to get the same results as the previous approach, it may be necessary to lower the perigee so much that it actually costs more to do this maneuver. The first issue is to discover at what elliptical orbit the lifetime is reduced to just under 25 years. Then, if this approach is possible, it will be necessary to find the Δv required to perform the maneuver and determine if it is cost-effective to take this approach.

By running the drag program I have created (see Appendix 1), it would be possible to determine the lifetime of the satellite for any orbit of any semi-major axis chosen. Unfortunately, the program I have designed is not perfected, and is currently unable to determine the precise lifetime for a given semi-major axis (notes on the errors and difficulties faced in this program also found in Appendix 1). Figure 6 shows a diagram of what such a maneuver would look like, with the initial orbit being the GTO discussed for the Centaur, and the final orbit being an elliptical orbit of a smaller semi-major axis, and probably a different eccentricity.

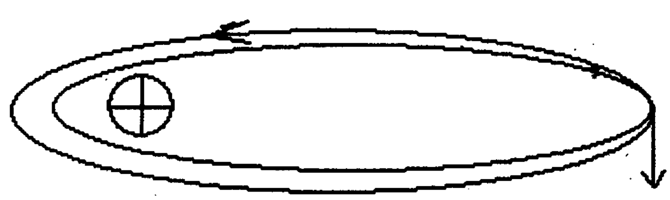


Figure 6: Lower the perigee with burn at apogee

Since the object of this research is limit the Centaur on-orbit lifetime after use, a point should be made. The Δv's determined here are found to decrease the lifetime to a pre-determined amount. However, one of the benefits of this type of maneuver is that if the burn is done with whatever residual fuel is left on board after use (the fuel that is normally de-gassed after detaching from the payload), the perigee will be reduced. Depending on how much fuel is left over, the lifetime will be decreased some amount below the original lifetime. Even though it is our goal to decrease the lifetime below 25 years, **any** decrease would be an improvement over the current procedure, which is to do nothing. With this in mind, some gambling can be done on the part of the designers when determining how much fuel to put aside for this burn without completely compromising the de-orbit attempt. This aspect of the results will be discussed again later.

Lowering Perigee (increase drag)

The final option I will evaluate is again only relevant for the geo-transfer orbit scenario. The idea is that there may be some way to decrease the orbit lifetime by increasing the drag. During the course of its geo-transfer orbit, the Centaur booster will periodically pass through the high-drag, low-earth environment. It is this environment that limits the on-orbit lifetime to as low as it is, as opposed to circular orbits at GEO, which have lifetimes on the order of thousands of years. Given its normal shape and no thought to orientation, the drag is enough that after approximately 75 years the rocket re-enters the atmosphere and burns up. If there is some way to increase the drag enough to decrease the orbit lifetime to an acceptable level (under the 25 years mark), it may be possible to avoid doing any Δv maneuvering at all! Because of this, this option may also present the most cost-effective solution to be addressed.

There are two different ways of looking at this type of solution. The first is to change the shape of the Centaur after use so that the average surface area that is feeling the atmospheric drag is increased enough to decrease the lifetime sufficiently. By avoiding the need for any additional attitude control or extra propulsion, the complexity of this de-orbit solution is fairly low. In addition, if the shape-changing device is not particularly heavy, it will not decrease the payload weight capabilities of the launcher. To determine if this is a viable solution to the problem, it is necessary to evaluate the drag that is normally present on the booster at these altitudes and look at how much we could theoretically increase the drag on the Centaur.

In order to determine the drag change needed by the Centaur in order to decrease its lifetime, it is first necessary to evaluate the drag as it normally acts on the booster, and see where there is room for "improvement." The changes in semi-major axis and eccentricity due to drag are:

$$\Delta a_{rev} = -2\pi(C_DA/m)a^2\rho_p\exp(-c)[I_0+2eI_1]$$

$$\Delta e_{rev} = -2\pi(C_DA/m)a^2\rho_p\exp(-c)[I_1+e/2(I_0+I_2)]$$

$$\text{lifetime} = -H/\Delta a_{rev} \qquad [20]$$

where the ballistic coefficient (m/C_DA) is taken to be 117782632.73 kg/km^2 [5], ρ_p is the atmospheric density at perigee (modeled as an exponential function, Appendix B), c is $^{ae}/_H$ (where H is the density scale height, modeled in Appendix C) and I_i are the Modified Bessel Functions [22], which are determined within the drag simulation program (Appendix A). The ballistic coefficient, which is the spacecraft quantity that affects drag, is defined as the mass divided by the quantity coefficient of drag (C_D) times the surface area. Since the program is not working up to specifications, as I have mentioned, it is not possible for me, at this time, to evaluate the exact ballistic coefficient necessary to achieve a lifetime below 25 years. However, from looking at the equations for drag, and assuming a lifetime of about 75 years, it can be seen that tripling the surface area or decreasing the mass by 1/3 (or some combination of the two) would decrease the lifetime enough. Since significantly decreasing the mass would mean a huge change in the

Centaur's design, I chose not to look at that aspect of decreasing the lifetime. However, there are ways of changing the area. If some sort of spring-loaded device were to cause the rocket body to "open up" and/or some sort of drag device were deployed, the atmospheric drag on the Centaur could theoretically be tripled due to the resultant decrease in the ballistic coefficient.

However, such a capability would require serious structural changes to the Centaur, as opposed to just boosting a smaller payload and saving fuel (as would be the case with a burn maneuver). Since there is little chance of selling such an idea for such a sweeping change, it will probably be best to abandon this idea. However, the idea of increasing drag to decrease the lifetime is not a lost cause. As mentioned previously, the Centaur has an internal navigation unit (INU) and the means of controlling its attitude (reaction control system, or RCS). Using this system, it should be possible to orient the spacecraft in such a way that the maximum surface area is perpendicular to the velocity and is most significantly affected by drag. Since there is currently no tracking of the Centaur after use, it is unknown what type of attitude the Centaur normally has during its long defunct lifetime after payload insertion. But by probability, we can be reasonably sure that such a maneuver would change the lifetime of the Centaur for the better. Since this maneuver is possible without any structural changes to the Centaur and can be done with minimal fuel (reserves usually de-gassed), this option should definitely be kept in mind.

DICUSSION OF LIMITATIONS

There are many limitations to the analysis done on the Centaur system. Since the perigee and apogee values that the Centaur booster is found in vary greatly with the mission (80-1500 nm for perigee, 5000-75000 nm for apogee) [5], the calculations done here are valid for the average values in some cases, for specific missions that I could find information on for others. The perigee and apogee values used for the main drag calculations were obtained from the exact numbers reported for the October 1997 DSCS III launch out of Cape Canaveral [5]. Further limitation on the altitude values are imposed by the lack of exact figures even for particular missions, and by variations in general caused by the moon's gravity, which can, under certain circumstances, raise or lower the perigee altitude by as much as 7-8 nm [5].

More specifically on the drag calculations, there are again several limitations on the validity of the results. The most obvious problem, of course, is that the program does not work at this time. However, the format of the program is valid, and estimations made by hand based on this algorithm are useful. When the program has been successfully debugged, there are several problems that may still present themselves when calculating spacecraft lifetimes. Values for the drag coefficient and cross-sectional area were obtained for the particular launch mentioned previously. These values can vary based on the orientation of the Centaur. Another source of possible limitation is in the modeling of atmospheric density and density scale height. Using Microsoft Excel, it is possible to take the table data for these values from several sources and derive a "best fit" solution for the data, so that interpolation of interior data can be made (as well as some extrapolation). Even though these "best fits" seem to work rather well, there is still some discrepancy from the real world, especially when extrapolation is done. Specifically, modeling the atmospheric density as an exponential function carries with it some limitations in accuracy. Variation due to solar activity fluxes also cause some problems in the accuracy of my atmospheric modeling.

Any analysis done on a particular system will have limitations based on approximations made for that system, and will have more pronounced limitations when applied to other systems. However, it should be kept in mind that despite the fact that these limitations exist, the conclusions drawn from them concerning the feasibility and effectiveness of particular de-orbiting procedures are **not** affected in a significant way. Although the exact numbers and lifetimes may be off, their relative cost, complexity, and effectiveness remain valid for most cases of interest. Also, the extrapolation to other systems is still very valid in a qualitative, if not quantitative, sense.

DISCUSSION OF APPLICATIONS

The applications of the data contained in this report are numerous, and affect the commercial and government interests of every space-faring country in the world. Even though the Δv, drag, and orbit lifetime analyses in this paper are specific to the Centaur's missions, this does not mean that the results are limited in scope to implementation on the Centaur.

With the increased popularity of GEO satellites, the use of geo-transfer orbits will increase as well. It is this type of orbit that presents one of the largest space debris problems for our near future. Even though the perigee/apogee altitudes and the specific qualities of the boosters will not necessarily be the same as, or even close to, those of the Centaur system discussed here, the solution procedures and relative results will most likely remain similar.

The extrapolation to other systems that this analysis provides will most easily be seen through brief examination of an example. As mentioned before, Japan has been making movements toward mitigating space debris in recent years. In 1994, they began initiating a change in the operation of the second stage of their H-II launcher [18]. For example, on one flight, the H-II second stage was de-orbited from a geo-transfer orbit of 251 km X 36,346 km to a 150 km X 32,298 km orbit [18]. This procedure was executed with an idle mode burn and caused the booster to re-orbit and burn up in the atmosphere in the next few years [18]. The same software used to evaluate the Centaur could also do this analysis. The de-orbiting procedure used here is very similar and, given the specific data on the H-II that I had for the Centaur, it would be possible to evaluate the Δv and drag equations for this booster as well. Similar analysis could be done on any of the world's GTO upper stages, or even on other high-orbit spacecraft or boosters. The whole process used in evaluating the Centaur can be used on any number of other systems.

With the increase in international concern over space debris, a "universal" model for evaluating the feasibility of de-orbiting procedures would be of great importance to any space-faring nation. As outlined in the space debris analysis section of this paper, there is already a need for more space debris control and prevention. This need will only increase over time unless there is immediate action. The model presented here is not extensive enough to provide legitimate reasons to choose a particular method or asses the costs involved for a given method. What this paper **does** provide is a very detailed analysis of one system, the Centaur, what options for de-orbiting are available at this time, and what their relative costs are in terms of risk, money, and complexity. This analysis should provide a clear view of the **need** for this kind of change and give a basis for future studies to be done by other organizations for their particular systems.

CONCLUSIONS

There are several conclusions to be reached by the end of this paper. The first concerns the problem of space debris as it faces us today. Another concerns what options are available in the fields of design, operations, and policy to mitigate this problem. The final conclusion concerns what options are available to change the design of the Centaur booster and which appears to be the best in terms of cost, complexity, and risk.

As demonstrated with the examples stated earlier in the paper, the problem of space debris increases every day. With every new launch, new debris material is placed into the "popular" orbits, providing a danger on their own and the potential for the creation of countless other pieces of debris if they were to break up or collide with another object. The CERISE collision, the constant small collisions the shuttle undergoes, and the damage other long-term facilities have undergone in the past should show just how bad the situation is becoming. The options for cleaning up the debris already in orbit are financially and technologically difficult, if not impossible. Therefore, the only clear solution for the present is to stop making more debris. It is exactly this attitude that leads to the discussion of the need to de-orbit the Centaur booster.

The second major section concerned the policies existing today and the policies/laws needed for true international space debris mitigation in the future. The common theme running through the "laws" present in our world today on this topic are that they are almost exclusively voluntary. These policies call for action on the part of the space community by appealing only to their conscience and intelligence, not to their pocket books. They call for groups launching satellites to avoid debris creation insofar as it is cost-effective. As we have seen with the Centaur, there is no such thing as a free de-orbit. All reasonable options incur some cost in terms of money, risk, complexity, and/or payload capacity. With this in mind, there is no way that any real change can take place in a world where a significant percentage of space launches are being done by commercial organizations engaged in competition with each other. Those companies who do attempt a degree of debris mitigation "enjoy" a distinct disadvantage against those who do not, giving them a good reason **not** to embark upon this important process to begin with. According to a recent estimate, $41 billion of the $77 billion spent on space commerce in 1996 was spent by private industry [21]. Any policy on space debris mitigation cannot ignore the contribution of the private sector in space commerce, or the competition that exists among them. Finding the most cost-effective solution is important to these thriving businesses and should be considered when international policies are decided upon. But when it comes down to it, the most important factor is that any policy should affect all businesses equally throughout the world.

This brings us to the Centaur analysis. The results in the relevant section of the text (Specific Topics of Review – Centaur 2nd Stage Launch System --- Solutions) provide a good look at the various design and operations scenarios that could successfully remove the Centaur as a space debris threat. Table 1 shows a brief comparison of the solutions presented. Here, I will only discuss what appears to be the best solution to each of the two orbits: the geo-transfer orbit and the super-synchronous orbit.

Solutions	Description	Pro's	Con's
GTO			
Energy weapon	Use directed energy to destroy booster or lower its orbit	-No change to booster necessary	-Difficult to achieve -Probably create more debris than it destroys
Circularize at apogee	Do three tangential burns (bi-elliptic transfer) to circularize at GEO + 300 km	-Low Δv -Completely removed as debris threat	-Three maneuvers means high complexity -Long time to complete maneuver (strain on batteries)
Circularize at perigee	Do single tangential burn to circularize orbit at perigee	-Only one maneuver -Partial completion still decreases lifetime	-High Δv
Lower perigee (burn)	Do single burn to lower perigee of elliptical orbit	-Only one maneuver -Partial completion still decreases lifetime	-High apogee means perigee must be lowered a lot (high Δv)
Lower perigee (drag)	Increase drag to decrease the lifetime (no change to orbit)	-No Δv needed	-Hard to decrease BC to three times as small -Transformation maneuvers are high complexity
SUPER-SYNCHRONOUS			
Graveyard orbit	Single tangential burn at apogee to circularize orbit above GEO	-Only one burn -Done immediately after payload separation (little strain on batteries)	-Slight loss of payload-boosting capacity

Table 1: Comparison of Solutions

From the results discussed in the aforementioned section, the best solution for the super-synchronous orbit appears to be the circularization at apogee. By doing the maneuver at such a high altitude, the Δv required is amazingly low, only about 0.4 km/s. Even though it takes a large amount of fuel to get to this altitude to begin with, this is required by the mission, so by keeping only a small amount of extra fuel on board the

Centaur (instead of burning it all as is usually the procedure), there is only a small loss of station-keeping fuel on the part of the payload, or a small loss in payload mass allowed. By keeping track of the efficiency of the Centaur during flight, it can be taken out to the highest altitude possible, until the remaining fuel is just enough to circularize at apogee. This allows for the payload to suffer little or no loss of lifetime if the Centaur performs to a high level of efficiency.

The other scenario is the geo-transfer orbit for the Centaur after separation from the payload. The approach of placing the Centaur in a graveyard orbit for the geo-transfer initial orbit required a Δv of about 1.5 km/s. Not only did this option require three separate tangential burns, but if the conditions prevented the Centaur from completing all three maneuvers, the resulting orbit would be just as dangerous as the original orbit, if not worse, since it would place it in an almost GEO orbit, where there is a lot of important "traffic." Also, this maneuver required that the Centaur be active for at least a day after payload insertion, a strain on the batteries powering the booster. However, the circularization at perigee required only **one** tangential burn to accomplish its mission and less than half as much time to complete (Alternatively, the lowering of perigee by doing a non-tangential burn may decrease the lifetime by the same amount with less or equal Δv). Although the circularization burn required a much higher Δv (2.45 km/s), the results are better than the original orbit even if only a portion of the burn is accomplished, since any decrease in the semi-major axis of the GTO will decrease the on-orbit lifetime. This allows designers to allot some of the extra fuel that is normally left over after the Centaur accomplishes its mission to this task, which in turn decreases the loss in payload-boosting capacity induced by the de-orbiting procedure. Furthermore, as mentioned previously, the Centaur could be oriented in such a way that the drag on the booster is maximized, thus decreasing the lifetime by using only a small amount of fuel from the attitude control subsystem (marginal fuel that is normally degassed) to position itself. In a worst-case scenario (severe lack of residual fuel after payload separation), the Centaur's lifetime would still be decreased somewhat from the original length. Without international policies enforcing the deorbit of boosters after use, it will be difficult to convince a corporation to voluntarily give themselves a competitive disadvantage. Making the process as painless as possible at first (by allowing this "gambling" with the amount of residual fuel left over), increases the likelihood that voluntary practices of this kind will be initiated. If and when international policies on space debris and the de-orbiting of spent spacecraft and boosters are put into effect, companies in all space-faring countries will be forced to do operations of this kind. In this situation, a decrease in efficiency does not affect the competitiveness of the companies in the international marketplace. But until such a time, the effects of de-orbiting capacity on the competitiveness of companies need to be strongly considered when encouraging such practices.

The problem of space debris will not go away on its own. Every study on the topic has driven this fact home. Although there are new ideas every year on how to improve spacecraft shielding and avoidance capacity, these abilities will have trouble improving as fast as the amount space debris increases, unless changes are made in the production of space debris. As yet, there is no reasonable way to dispose of existing debris, so the only positive effect we can have on the problem is through prevention. One of the most common sources of space debris are spent boosters left in orbit. With the increased interest in GEO slots, boosters left in geo-transfer orbits will be a problem for the foreseeable future. With this in mind, the de-orbit/disposal of boosters like the Centaur is, and will continue to be, an important topic. This paper has presented the need for immediate international action on the problem of space debris and has presented a strong basis for future study on the exact means of de-orbiting/disposing of the Centaur second stage launcher after use.

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18) http://www.un.or.at/OOSA_Kiosk/spdeb/spdeb95/spdeba.html

19) http://www-sn.jsc.nasa.gov/Debris/part3c10.html

20) Larson, Wiley J. and Wertz, James R. (ed.), Space Mission Analysis and Design (2nd edition), Microcosm, Inc., California, 1992.

21) Oberg, Alcestis, "Who needs NASA? Private sector can do it cheaper," USA TODAY, Monday, April 6, 1998, p13A.

22) Press, William H. et al, Numerical Recipes in FORTRAN (2nd edition), Cambridge University Press, U.S.A., 1992.

APPENDICES

A) Drag Simulation Program

B) Spreadsheet determination of atmospheric density as a function of altitude [data from reference 20]

C) Spreadsheet determination of density scale height as a function of altitude [data from reference 20]

```
//                              APPENDIX A

//Humphrey Bohan
//Program for Creative Investigation
//
/*  This program computes the values for the change in semi-major
    axis and eccentricity per revolution due to drag.  In the process,
    the program must compute the first three modified bessel functions
    (I0,I1,I2) [22].  The lifetime of the satellite can then be computed and
    variables can be adjusted to see their effects on the lifetime of the
    satellite.

    NOTE:   This program is created to run through variations in the
            ballistic coefficient until the lifetime requirement is met.
            I believe that the lifetime of the Centaur rocket body in GTO
            should be longer than the 18+ years I am getting right now.  My
            conversations with Dr. Fosha [6] indicate the lifetime should be
            on the order of about 75 years.  Since this is not the lifetime
            that this program is currently calculating, the full potential
            of the simulation cannot be explored.  However, it is useful in
            doing qualitative calcuations of the effects of certain changes
            to the ballistic coefficient.  It is possibly a combination of
            modeling the atmosphere as an exponential funciton, modeling the
            scale height as a logarithmic function, and using Bessel functions
            with such a large arguement that has lead to many of the
            discrepancies found in using this simulator.

            The example I have left the program in is in using this simulator
            to determine the ballistic coefficient necessary to cut the lifetime
            in half.
*/

#include <stdio.h>
#include <math.h>
#include <iostream.h>
#include <fstream.h>
#include <stdlib.h>

#define Pi 3.1415927
#define Rearth  6378.136        //km
#define mu 398600.0             //km^3/sec^2

double abs(double);
double besselI0(double);
double besselI1(double);
double besselI2(double);
double find_density(double);
double find_H(double);
double BCoeffFind(double,double);

double lifetime,a,initial_lifetime;      //want them global so I can chart their
                                         //values outside the functions

void main(void)
{
    double BallisticCoeff,saveBC;
    long double increment;
    int i;

    ofstream out("output.txt");
```

```
    BallisticCoeff=117327246.8; //kg/km^2 reported by Lockheed-Martin
    saveBC=BallisticCoeff;
    increment=1000000.0;

    for (i=1;i<=1;i++)
    {
        lifetime=10000.0;
        BallisticCoeff=BCoeffFind(BallisticCoeff,increment);
        increment=increment/10.0;
    }

    out<<"inital ballistic coefficient = "<<saveBC<<" kg/km^2\n";
    out<<"inital lifetime for orbit = "<<initial_lifetime<<" years\n";
    out<<"semi-major axis = "<<a<<" km\n\n\n";
    out<<"to get a lifetime of "<<lifetime<<" years, the \n";
    out<<"final ballistic coefficient must be "<<BallisticCoeff<<" kg/km^2\n\n";

    out.close();
}
/***************************FUNCTIONS**********************************/
double BCoeffFind(double BC,double increment)
{
    double I0,I1,I2;
    double H,e,c;
    double bessel_a_factor,bessel_e_factor;
    double density,perigee_alt;
    double delta_a,delta_e;
    double period;
    int iterations;

    iterations=1;
    initial_lifetime=1.0;
    a=24343.336;                    //km assuming 227 km X 35,703.4km
    a=7000.0;                       //625 years
    e=0.728667591;
    e=0.05;
/*  m=3954 or 4150 lbm
    Cd=2.2
    A=78.5 ft^2*/

    while (lifetime>initial_lifetime/2.0)
    {
        perigee_alt=a*(1.0-e)-Rearth;

        H=find_H(perigee_alt);              //find scale height

        c=a*e/H;

        I0=besselI0(c);
        I1=besselI1(c);
        I2=besselI2(c);

        bessel_a_factor=I0 + 2.0*e * I1;
        bessel_e_factor=I1 + e/2.0 * (I0+I2);

        density=find_density(perigee_alt);  //find density

        delta_a=-2.0*Pi*(1.0/BC)*a*a*density;
        delta_a=delta_a*exp(-c)*bessel_a_factor;
```

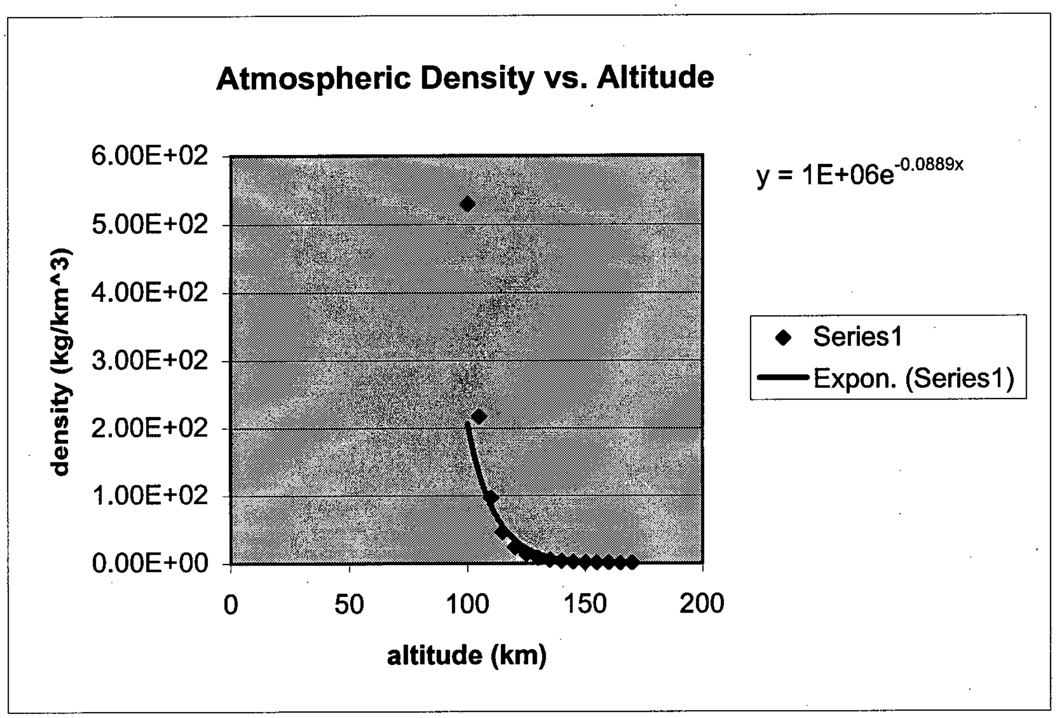
```
        delta_e=-2.0*Pi*(1.0/BC)*a*density;
        delta_e=delta_e*exp(-c)*bessel_e_factor;

        period=2.*Pi*sqrt(pow(a,3)/mu);

        lifetime=-H/delta_a;                        //approximation for lifetime
        lifetime=lifetime*period;                   //seconds
        lifetime=lifetime/60.;                      //minutes
        lifetime=lifetime/60.;                      //hours
        lifetime=lifetime/24.;                      //days
        lifetime=lifetime/365.25;                   //years

        if (iterations==1)
            initial_lifetime=lifetime;

        iterations++;

        BC=BC-increment;
    }
    BC=BC+2.*increment;
    return BC;
}
/**************************************************************************/
double abs(double x)
{
    double temp;

    if (x<0)
        temp=-x;
    else
        temp=x;

    return temp;
}
/**************************************************************************/
double besselI0(double x)
{
    double bessi0,bessi0temp,bessi0temp2,ax,y;
    double p1,p2,p3,p4,p5,p6,p7;
    double q1,q2,q3,q4,q5,q6,q7,q8,q9;

    p1=1.0;
    p2=3.5156229;
    p3=3.0899424;
    p4=1.2067492;
    p5=0.2659732;
    p6=0.0360768;
    p7=0.0045813;
    q1=0.39894228;
    q2=0.01328592;
    q3=0.00225319;
    q4=-0.00157565;
    q5=0.00916281;
    q6=-0.02057706;
    q7=0.02635537;
    q8=-0.01647633;
    q9=0.00392377;

    if (abs(x)<3.75)
```

```
    {
        y=(x/3.75)*(x/3.75);
        bessi0=p1+y*(p2+y*(p3+y*(p4+y*(p5+y*(p6+y*p7)))));
    }
    else
    {
        ax=abs(x);
        y=3.75/ax;
        bessi0temp=exp(ax)/sqrt(ax);
        bessi0temp2=q1+y*(q2+y*(q3+y*(q4+y*(q5+y*(q6+y*(q7+y*(q8+y*q9)))))));
        bessi0=bessi0temp*bessi0temp2;
    }

    return bessi0;
}
/***************************************************************************/
double besselI1(double x)
{
    double ax,y,bessi1,bessi1temp,bessi1temp2;
    double p1,p2,p3,p4,p5,p6,p7;
    double q1,q2,q3,q4,q5,q6,q7,q8,q9;

    p1=0.5;
    p2=0.87890594;
    p3=0.51498869;
    p4=0.15084934;
    p5=0.02658733;
    p6=0.00301532;
    p7=0.00032411;
    q1=0.39894228;
    q2=-0.03988024;
    q3=-0.00362018;
    q4=0.00163801;
    q5=0.01031555;
    q6=0.02282967;
    q7=-0.02895312;
    q8=0.01787654;
    q9=-0.00420059;

    if (abs(x)<3.75)
    {
        y=(x/3.75)*(x/3.75);
        bessi1=p1+y*(p2+y*(p3+y*(p4+y*(p5+y*(p6+y*p7)))));
    }
    else
    {
        ax=abs(x);
        y=3.75/ax;
        bessi1temp=exp(ax)/sqrt(ax);
        bessi1temp2=q1+y*(q2+y*(q3+y*(q4+y*(q5+y*(q6+y*(q7+y*(q8+y*q9)))))));
        bessi1=bessi1temp*bessi1temp2;
        if (x<0.0)
            bessi1=-bessi1;
    }
    return bessi1;
}
/***************************************************************************/
double besselI2(double x)
{
    double n,bessi2;
```

```
    n=2.0;

    bessi2=-(2.0*n/x)*besselI1(x)+besselI0(x);

    return bessi2;
}
/*********************************************************************/
double find_density(double alt)
{
    double density;

    density=1.0e6*exp(-0.0889*alt); //answer in kg/km^3

    return density;
}
/************************************************************************/
double find_H(double alt)
{
    double H;

    H=35.28*log(alt)-152.47;

    return H;
}
/************************************************************************/
```

APPENDIX B

ALTITUDE	DENSITY
100	5.30E+02
105	2.17E+02
110	9.66E+01
115	4.65E+01
120	2.44E+01
125	1.38E+01
130	8.484
135	5.563
140	3.845
145	2.774
150	2.07
155	1.587
160	1.244
165	9.93E-01
170	8.04E-01



APPENDIX C

ALTITUDE	H
100	5.9
150	25.5
200	37.5
250	44.8
300	50.3
350	54.8
400	58.2
450	61.3
500	64.5